Sound Velocity Profile Estimation from High-Frequency, High Resolution Ahead Looking Sonar Data

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LONG-TERM GOAL

The long term goal is to develop and implement a software module that could be inserted into the processing stream of the new generation of high-frequency, high-resolution (HFHR) ahead-looking sonar (ALS) on submarines and potential UUVs, towed-bodies, and surface craft that would estimate the sound velocity profile (SVP) in real time. Since a non-uniform SVP distorts the echo data from the sonar, the SVP estimation module would use distortion in the data from the sonar to continually update the SVP until the measured distortion is removed.

The goal of this project is to assess the feasibility of estimating the SVP from the distortion on a ping-to-ping basis as the sonar passes over the seafloor.

OBJECTIVES

The first objective is to emulate at a sufficient level of detail the data collected on an ALS system, the distortion induced by a non-uniform SVP, and the monopulse processing in the new generation of ALSs that computes the arrival angles along with the time of arrival for every echo return in the scene.

The second objective is to develop an algorithm or inversion program that would use the output of the emulation (as if sonar was passing over the seafloor) and compute the SVP to remove the distortion in the scene. Two errors are measured. First, internally the algorithm measures the distortion of the seafloor (actually the distortion of the tracks of objects on the seafloor as the vehicle approaches) as the SVP estimate improves and second, external to the estimation algorithm, the error between the actual and estimated SVPs is measured to evaluate the algorithms performance.

APPROACH

Emulation of Sonar Operation: The emulation of the overall ALS data collection process is composed of two major components, the determination of the SVP induced distortions and the simulation of the processing in the ALS system. The SVP distortions are computed with a ray-tracing program that models the SVP with a number of constant gradient layers (the ray approximation of the acoustic propagation is sufficient, since in the long-term goal the application is for high frequency systems). The new generation of HFHR sonar systems track objects from ping-to-ping in range, bearing, and ray arrival angle. Without SVP induced distortions the object tracks could be converted to a full cylindrical coordinate system, range, bearing, and depth. For this project, the sonar system emulation only required a single bearing and the "sonar tracks" were determined by calculating the arrival times and arrival angles of each ray in the ray-trace program. These two components of the emulation provided the inversion program with the same inputs as the final application sonar system. The inputs are the many multi-ping arrival times and arrival angles from objects through a distorted sound field.

Problem Restrictions: The focus of this project was on downward refracting profiles. This case was selected because it was expected to simplify the inversion algorithms and it is the most common class of profiles encountered by HF ALS systems that, due to attenuation, tend not to have any channeling effects. Bounce paths were also not addressed directly in this project. At first they were not addressed to simplify the inversion problem, but as the inversion algorithm matured, it was recognized that this approach, described later, may be able to recognize the bounce paths and use them for more information about the SVP or just cull them out and ignore them.

Inversion Scheme Selection: Determining the SVP for the echo return travel times and arrival angle is a multi-variate non-linear inversion problem. No direct inversion method was found, so two non-linear optimization schemes were considered. In both schemes, the SVP was approximated by constant gradient layers. In the first of the two schemes, an analytic expression was derived for the travel time from the sonar to the sea floor as a function launch (or arrival) angle and the SVP gradient parameter set. A error functional was written in terms of the actual times, the "actual" SVP, and the arrival times through the approximation to the SVP. Analytic forms of the error functional, its gradient, and quadratic term would be used in a second order extension of a Newton-Raphson numerical optimization algorithm. It was determined that two analytic expressions for the upper and lower parts of the SVP (i.e., above and below the sonar) would be needed. Because of the complexity of the final algorithm description, a second scheme was investigated. The second scheme, a simulated annealing optimization algorithm, required a single description for the whole profile and was selected for development.

The simulated annealing algorithm starts at a random configuration of sound speeds and continually perturbs the current "best" sound speed profile. The cost of a guess is the RMS deviation of the ray end points from the expected horizontal trace. If the cost of a new guess is better than the "best" guess, the new one is always favored. However, the algorithm accepts worse guesses with a probability

$$P(C_{guess}) = \exp\left(-\frac{\left|C_{best} - C_{guess}\right|}{T}\right)$$

where T (a variable analogous to the temperature of a cooling metal) decreases geometrically with each iteration. The result is that the algorithm "climbs uphill" every once in a while to see if there are deeper valleys elsewhere in the cost function, avoiding local minima (to cross ridges in the cost function).

The maximum number of iterations, the initial value and rate of decrease of T, and the method of perturbing solutions are important parameters in making the algorithm work. The literature available offers no strict advice on picking these parameters a priori, but good values can be found by experimenting with the particular application on a problem with a known solution.

Algorithm Development and Testing: With an emulation software in place and the selection of the inversion algorithm completed, the algorithm was tested by (1) selecting a test SVP, (2) running the ray trace to determine the travel times and arrival angles, (3) running those rays (travel times and arrival angles) through the assumed SVP, (4) determine the error due to distortion, (5) update the assumed SVP to reduce the error, and (6) steps 3 through 5 until the error is minimized. The algorithm was first developed and tested on simple SVPs (e.g., constant gradient, a few constant gradient layers, simple smooth non-linear profiles like quadratics) then it was evaluated on smoothed versions of measured SVP, and later with measured SVPS.

Error Functionals: Two error functional were used in the evaluations. The first error functional measures the distortion from straight in the object tracks (or bottom in a flat bottom case) and the second error functional measures the error between the test SVP and the assumed SVP. The first error functional is used in the optimization procedure since this would be used in the real application. The second functional is used for assessment of the overall inversion performance but is not used in the optimization procedure since this error could not be known in an actual implementation.

WORK COMPLETED

1) Implemented a ray trace program appropriate for this task and embedded the extraction of the sonar measurements to form the system emulator. 2) Selected simulated annealing for the non-linear optimization procedure since it could be formulated for the whole water column. 3) Implemented a simulated annealing routine and coupled it with the emulator. 4) After some initial inversion trials, a technique was developed to divide the inversion problem into stages that significantly improved the convergence speed and robustness. 5) Continued development and tested the inversion procedure on an expanded set of SVPs. 6) Concluded that the procedure is feasible but issues of data noise and data noise characteristics need to be addressed.

RESULTS

The goal of this project was to develop an inversion algorithm to determine the SVP from acoustic backscatter data off the seafloor from a HFHR ALS system. The inversion algorithm was developed and tested on a series of simple SVPs (iso-velocity, constant gradient, and near quadratic), some smoothed SVPs that had been derived from historical data from different regions in the world, and some directly measured SVPs.

First, it was discovered that, with an error functional based only on the flatness of the object tracks, the inversion algorithm needed an additional piece of information to get the overall scale of the scene correct. That is, the tracks would be flat but at the wrong depths. This ambiguity can be removed with either the actual depth of the tracks or a single point measurement of the SVP. The single point SVP measurement was selected since it is easy to get in most actual applications.

It was also discovered that the inversion procedure should be divided into stages. The lower part of the SVP, below the sonar, should be determined first using the rays with a negative arrival angle. This works well because these rays travel though each layer once and only once, and the relationship between the lower part of the SVP and the distortion of the seafloor or object tracks appears to be well behaved. The second stage in the algorithm uses the upper traveling rays which pass through most of the upper SVP layers twice and the lower layers once. Only the upper layers are estimated since the others were determined in the first stage. The final stage allows all the layers to pertebate a bit. Figures 1 and 2 show the algorithm part way through the optimization process and at completion.

Fortunately, this particular division of the inversion procedure into determining the lower and upper SVP sections separately is not artificial, but can be implemented in a real application. One only needs divide the rays by their arrival angles.

Overall, it appears that it is feasible to compute the SVP from data from the new generation of high-frequency high-resolution ahead looking sonar systems. The developed procedure was tested on many sample SVPs. The algorithm would consistently converge to less than 1% SVP error for the lower section of the profile. Convergence on the upper section is less consistent. When it converges, the errors are similar to the lower section; however, it does not always converge. Fortunately, the algorithm recognizes the lack of convergence and can provide a "quality indicator." The algorithms have not been tried on real data. In the real data, there will be measurement error whose affects on the inversion algorithms is unknown at this time, but these affects may be mitigated by tracking many objects and averaging out the noise.

IMPACT/APPLICATION

If these algorithms are matured to work on real data, then platforms with the newer generation of ALS systems could compute the SVP of their environment in real time without launching any external probes. The computed SVPs could be used by the ALS system to adjust their internal parameters to improve their performance, the SVPs could be passed to other systems, or stored and passed onto other platforms.

TRANSITIONS

These algorithms could be tested in the HF APB process for the submarines and inserted into the ARCI-P4 system on the improved 688 boats, onto the Virginia class boats, and onto the early flight 688s with the BQS-15a sonar suite. The algorithms could also be implemented within product improvement upgrade that is being planned and/or discussed for LMRS, RMS, and SQQ-32.

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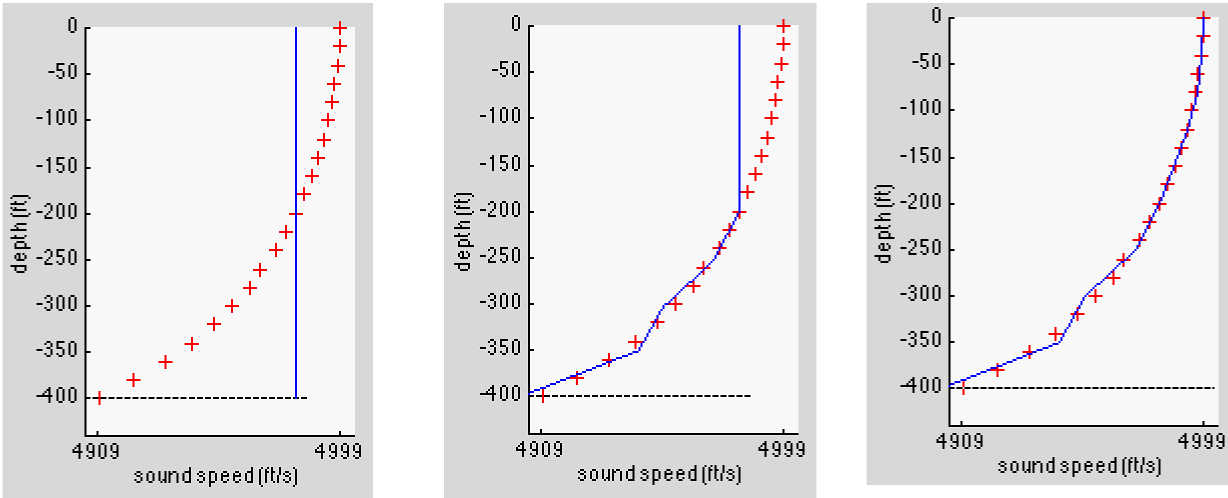

Figure 1: Steps in Annealing Process for a Simple SVP: Actual SVP indicated by red pluses. The current estimate is shown by a blue line. The three figures show the initial estimate, a uniform SVP, the estimate after computing the lower section, and the final estimate. In this example, the optimization algorithm completed the convergence to the final solution.

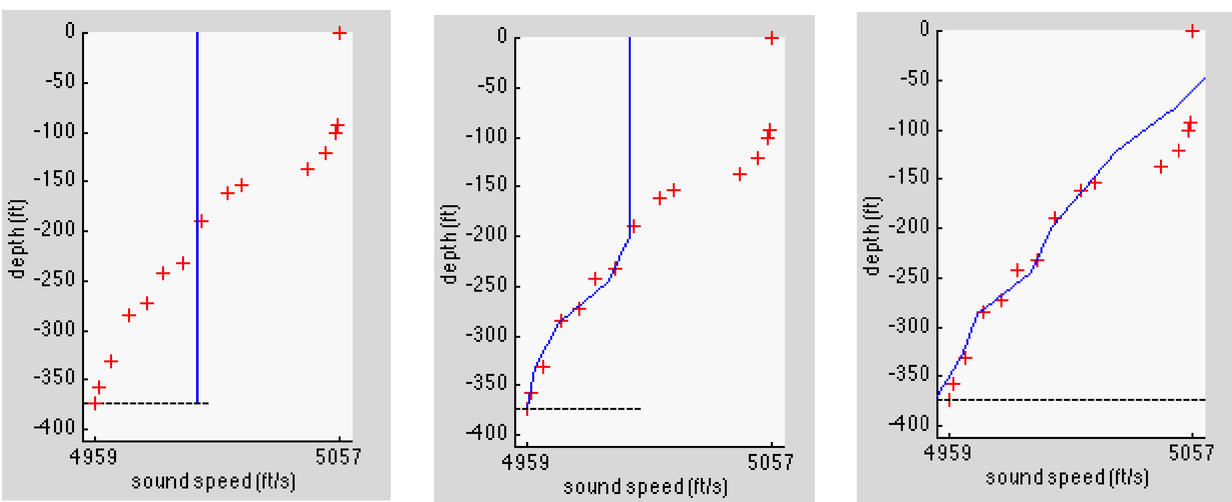

Figure 2: Steps in Annealing Process for a Historical SVP Actual SVP indicated by red pluses. The current estimate is shown by a blue line. This example shows a case were the algorithm was not able to converge. Typically, it converges on the lower section but can not find a good solution for the upper section. The lack of convergence in the algorithm provides a factor to indicate the quality of the SVP estimate.